SPOT SIZE COMPARISONS ON OIL- AND WATER-SENSITIVE PAPER

R. D. Fox, M. Salyani, J. A. Cooper, R. D. Brazee

ABSTRACT. Water- and oil-sensitive paper (WSP and OSP) was attached to tree leaves and to a tower bracket between trees. Petroleum spray oil was applied at a constant rate in four concentrations of spray oil in water (1:5.9, 1:10, 1:50, and 1:100) with 17 treatments. WSP and OSP were sprayed in a laboratory with 8001 and 8004 flat fan nozzles. Spot size on oil- and water-sensitive paper, placed at the same location for the same spray condition, were compared by assuming the spots came from the same droplet size population. The spot sizes were sorted by size and divided into 25 classes with the same number of spots in each class. The mean size of each population was calculated for each size class and the ratio of water to oil spots was calculated. To reduce the effect of spot overlap, only sprayed samples with low populations (less than 20% coverage) of water and oil spots were used. Measured spot size ratios were compared to ratios calculated from droplet diameter ratios computed from volume mixtures and from known spread factors on water and oil sensitive paper. Water:oil spot size ratios predicted using known mixture ratios and spread factors agreed quite well with laboratory measured spot size ratios. However, spot size ratios measured for field experiments did not agree with predicted values. This may have been due to larger water spots touching, or oil spots separating into several globules as the water portion of the spray droplet evaporates.

Keywords. Spray, Droplets, Spread factor, Orchard spraying.

Measuring spray deposits on plant targets or on simulated plant targets is an important technique to evaluate spray application methods. In addition to pesticide coverage on leaves, there have been many tracer materials and artificial targets used to collect the spray droplets. One of the most convenient methods is to use commercially available water-sensitive paper. Water in the spray stains the paper coating and the spot size can be observed or measured. Spread factor relationship between spot and droplet diameters for water or other spray mixtures can be measured (Franz, 1992; Ciba-Geigy 1994a, b; Salyani and Fox, 1999). A disadvantage of WSP is the overlapping of spots in many field experiments at normal field application rates.

Other research has considered several ways to evaluate spray deposits on collectors. Giles et al. (1989) used a colorimeter to quantify spray deposits from an air-carrier sprayer. WSP targets were mounted on poles in the open and within peach-tree canopies. Bateman (1993) provided a review of methods of evaluating spray coverage. He also described a scoring system used with spot coverage targets. The system was mainly designed for treatments with fairly uniform spot sizes, but the target score was related to spot density and spot size.

Franz (1993) used a hand-held image scanner to obtain images from stained spray droplet deposits. He found the hand-held system had similar problems to camera-based systems, but if proper procedures were followed carefully, acceptable spot size results could be obtained.

In field experiments where nine different air-blast sprayer treatments were applied to citrus trees, Salyani and Fox (1999) collected water- and oil-sensitive papers for image analysis. OSP and WSPs were attached to the top and bottom surface of leaves at four locations within the canopy. Additional papers were placed on the top, bottom, and vertical surfaces of holders at two elevations on a pole on the tree-row centerline, midway between trees. After spray had dried on OSPs, they were treated to ‘fix’ the spot size and prevent size change with time (Salyani, 1999).

Salyani and Fox (1999) measured spread factors for water and oil using pure water and pure oil droplets applied to the respective sensitive papers. The major objective of that study was to measure spray deposit patterns for the different spray treatments. However, a second goal was to compare the spot size measured on OSP with those measured on WSP. Spot size is difficult to measure accurately on targets with high spot populations, as spots tend to touch and are interpreted as one spot by imaging software. It was hoped that by applying the oil at low rates, the OSP would have smaller spots and, therefore, would provide better resolution among treatments. Statistical analysis of the treatments showed significant differences in some of the WSP and OSP results.

In this study, we used the WSP and OSP targets from 17 orchard and 4 laboratory treatments to obtain a relationship between water and oil spot size. The assumption

Article was submitted for review in March 2000; approved for publication by the Power & Machinery Division of ASAE in September 2000.

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was made that spray deposits on each collector–pair (WSP and OSP) were exposed to the same spray cloud for each sprayer treatment. Thus spray–droplet size distribution, wind conditions, leaf movements, etc. should have been the same for each collector pair. The objective of this study was to calculate the ratio of WSP to OSP spot sizes for several concentrations of oil in water mixtures. The goal was to establish a relationship between spot size and coverage of OSP and WSP, so that oil–water sprays could be used to differentiate with increased sensitivity among spray applications wherein coverage saturated WSP.

Methods and Materials
Experimental Procedures
Field Experiments
Details of experimental procedures used to spray the WSP and OSP are given in Salyani and Fox (1999). Briefly, 17 sprayer treatments were made to citrus trees with two conventional (axial–flow fan) sprayers and an air curtain (cross–flow fan) sprayer. Conventional sprayers applied water with spray oil (Sunspray–7E petroleum oil, Sun Refining and Marketing Co.) added, at application rates of 375, 1875, and 3750 L/ha (40, 200, and 400 gal/acre). The air curtain sprayer applied 220 L/ha (23.5 gal/acre). Oil was applied at a constant rate of 37.5 L/ha (4 gal/acre) for all applications. Applications made with all nozzles on the sprayer targets was to match each treatment (location, sprayer, and replication) individually. The spot diameters measured on OSP and WSP were arranged in diameter size order from smallest to largest. The spots were not corrected for spread factor. Then, spots on individual oil– and water–targets were divided into 25 classes with the same number of spots in each class. The mean droplet size of spots in each size class was determined for both oil– and water–target pairs and the ratio of water–spot diameter to oil–spot diameter for each class was calculated.

After the mean spot size was calculated for each of the 24 classes for WSP and OSP, spot size ratios were calculated. Each pair of samples produced different spot sizes and it was difficult to average across samples or to present the results as a function of water spot size. Therefore, a digital extrapolation method was used to assign a computed spot size ratio value to a range of fixed water spot size classes, ranging from 80 to 1100 μm. After measured spot size ratios for each pair of targets were transformed into the fixed water spot size basis, then average water:oil spot ratios could be calculated across all samples in each treatment. To simplify graphing, 50 values of water spot size were used. Some treatments did not have spots over the entire range so less than 50 values were plotted in these cases. This analysis procedure and inherent characteristics of spot size measurement with imaging systems introduce several limitations to this technique.

Assumptions of Method
1. The spray droplet distribution produced by the sprayer is the same as the distributions collected on the water sensitive paper and on the oil sensitive paper.
2. Oil in the water does not affect spot size on the water sensitive paper.
3. Oil spots all reflect the actual amount of oil in impacting droplets of oil/water emulsion, i.e., oil spots all form from a single oil globule in each spray droplet.
4. The smallest droplets that are not measured on oil– and water–sensitive paper do not have a significant effect on the number of spots in the large size classes of the spot size distributions on collector papers.

5. The larger spots that result from drop overlap or contact are few for the samples chosen, and do not have a significant effect on the spot size distribution.

**Collectors Selected for Analysis**

The criteria described above for selecting collectors (targets) with suitable spot distributions for water:oil spot size comparisons were applied to 504 target pairs and the following targets were selected for this study:

- 220 L/ha (23.5 gal/acre) – the sprayer used for this application rate utilized a rotary atomizer that produced smaller droplets that the other treatments. Thus, at most locations, WSPs had coverage patterns that met the above criteria. Of course, a lower percentage of sprayed droplets could be measured for these targets, because more spots were below the size threshold measured. This sprayer also used the greatest portion of oil to water in the sprayed mixture; 13 of 24 samples with targets on a tower, and 14 of 32 samples with targets on leaves were used.

- 375 L/ha (40 gal/acre) – only targets with a uniform nozzle arrangement (the same nozzle size was mounted at all locations on the sprayer) were considered; 15 of 112 targets were used.

- 1875 L/ha (200 gal/acre)– only targets with a uniform nozzle arrangement were considered; 13 of 224 targets were used.

- 3750 L/ha (400 gal/acre)– only targets with a uniform nozzle arrangement were considered; 4 of 112 targets were used.

Targets selected from the high spray application rates were those targets that received poor WSP coverage. These targets were usually located in the inside of the tree canopy where variability between water and oil deposits is likely to be greatest. As can be seen from the number of targets selected, those with the rotary nozzles provided the most usable samples.

**Calculation of Predicted Spot Size Ratios**

Predicted spot size ratios were calculated from the water:oil proportion in the mixture using the water spread factor relationship measured by Salyani and Fox (1999). The oil spread factor relationship was determined by measuring the size of airborne oil droplets and OSP spots with an imaging system.

The calculation procedure for predicted spot size ratios is shown in spreadsheet form in table 1. The following relationships were used:

- Droplet diameter ratio = (volume ratio)$^{0.333}$.
- Spot diameter ratio = (Droplet diameter ratio × water spread factor/oil spread factor).

Spot to droplet regressions were:

$$D_o = 1.71 S_o^{0.723} \text{ and } D_w = 0.95 S_w^{0.91}$$

where D is droplet diameter, S is spot diameter, and the subscripts o and w represent oil and water, respectively.

**RESULTS**

**Predicted Water: Oil Spot Size Ratio**

Predicted water:oil spot size ratios for the spray tank mixture ratios used in this study are shown in table 1 for droplet sizes of 200 and 500 μm. Because the spread factor for large oil drops on OSP is much greater than for WSP, oil spots are expected to be larger than water spots in some cases. For example, in this study this result occurs for spot sizes greater than 400 μm with oil:water volume ratios of 1:5.7 and for spots greater than 500 μm with volume ratios of 1:5.7 or 1:10. For mixture ratios of 1:50 and 1:100, water spot diameters are expected to be about 3 to 6 times greater than oil spot diameters.

**Calculated Water: Oil Spot Ratios**

The mean of water:oil spot ratios for all selected targets for each application rate as a function of water spot size is shown in figures 1, 2, 3, and 4. The error bars represent one standard deviation. Spot size ratios for laboratory experiments are also plotted in these figures. Error bars for laboratory experiments are not shown for a clearer presentation of the graph. The predicted water:oil spot ratios for associated volume mixture ratios are also plotted in these figures. In all cases, the trend in measured water:oil spot size ratio for field experiments was to increase somewhat with increasing water spot size. However, predicted ratio always decreased with increasing water spot size. Water:oil spot size ratios measured for laboratory experiments often were about constant or decreased slightly with increasing water spot size.

Deposit spots on water– and oil–sensitive papers placed on holders on towers between rows were expected to be more alike than deposits than papers mounted within the canopy. Within the canopy, leaves may cover one paper and not the other, depending on air currents from the sprayer jet and leaves at the edge of the canopy may filter out some large droplets. Therefore, figure 1 should contain the best data available for this study. As can be seen in figure 1, oil spots were expected to be larger than water spots for spot sizes greater than 400 μm for laboratory experiments and 500 μm for experiments with the air–curtain sprayer. Water:oil spot ratios calculated from measured spots agreed fairly well with predicted spot ratios in laboratory studies for spot sizes greater than 200 μm, but not so well with field experiments.

### Table 1. Predicted ratio of water to oil droplet sizes for each spray mixture ratio

<table>
<thead>
<tr>
<th>Spray Treatment L/ha (gal/acre)</th>
<th>Volume Ratio: Water Application Rate/Oil Drop</th>
<th>Droplet Diameter Ratio: Water Spot/Oil Drop</th>
<th>Spot Diameter Ratio: Water Spot/Oil Spot</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 (23.5)</td>
<td>5.9</td>
<td>1.80</td>
<td>1.3</td>
</tr>
<tr>
<td>375 (40)</td>
<td>10</td>
<td>2.15</td>
<td>1.6</td>
</tr>
<tr>
<td>1875 (200)</td>
<td>50</td>
<td>3.68</td>
<td>3.5</td>
</tr>
<tr>
<td>3750 (400)</td>
<td>100</td>
<td>4.64</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Spread factor for oil = $S_o / D_o$ and spread factor for water = $S_w / D_w$. 

Vol. 17(2): 131–136
Figure 1. Mean water:oil spot size ratio with 220 L/ha (23.5 gal/acre) application rate to collectors on tower between trees. Mean is of 13 samples. Error bars represent one standard deviation. Solid line is predicted ratio from mixture proportions (1:5.9) and spread factors. Spot size ratios for laboratory experiments with 8001 and 8004 nozzles with oil:water mixture ratio of 1:5 are also shown.

Figure 2. Mean water:oil spot size ratio with 220 L/ha (23.5 gal/acre) application rate to collectors on leaves. Mean is of 14 samples. Error bars represent one standard deviation. Solid line is predicted ratio for oil:water mixture ratio of 1:5.9.

The calculation method used here forced the water:oil spot ratio to be near 1 for the smallest classes considered. The detection limit on the imaging system identified the same minimum spot size on both WSP and OSP. Because oil spots were expected to be smaller than water spots, this lower limit on spot sizes means that more oil than water spots were below the size detection limit. An example of the small droplet detection effect is shown in figure 5. Log–normal distribution plots are shown for geometric mean spot sizes of 100 and 200 μm. Eliminating all spots less than 80 μm has a much
Laboratory results were nearer to expected because the spray the water:oil spot size ratio to be greater than expected. Drplet overlap and multiple oil droplet deposits would cause area coverage or volume of spray on OSP targets. Both water less effect on studies wherein spot images are used to estimate results of this study, which compared spot sizes, it would have large spot on the OSP. While this phenomenon affected the globules then formed two or more small spots instead of one more globules within the water droplet as it dried. These observed that sometimes oil droplets separated into two or more droplets. Also while watching sprayed mixtures dry, we to the greater possibility of water droplets touching for larger measured ratios for the field experiments was probably due to the greater possibility of water droplets touching for larger droplets. Also while watching sprayed mixtures dry, we observed that sometimes oil droplets separated into two or more globules within the water droplet as it dried. These globules then formed two or more small spots instead of one large spot on the OSP. While this phenomenon affected the results of this study, which compared spot sizes, it would have less effect on studies wherein spot images are used to estimate area coverage or volume of spray on OSP targets. Both water droplet overlap and multiple oil droplet deposits would cause the water:oil spot size ratio to be greater than expected. Laboratory results were nearer to expected because the spray application rate was kept low enough to prevent most droplet overlap, and droplets produced by the nozzles chosen had a large percentage of droplets less than 400 μm.

Similar results were found for WSP and OSP stapled to leaves, as shown in figure 2. Again measured spot size ratio increased with spot size, whereas, based on oil concentration in the mixture and spread factor, the ratio was expected to decrease with increasing spot size. This effect is probably due to the same reasons given for the targets mounted on towers between the trees.

Measured water:oil spot size ratio for oil:water mixtures of 1:10 are shown in figure 3. Results are similar to those shown for sprayed at mixtures of 1:5.9, shown in figures 1 and 2, except laboratory and predicted results are closer to the field results. This improved agreement between laboratory and field results is probably due to the selection of field treatments for use in these calculations. Only treatments with low percent area coverage of water were selected. Thus treatments selected were those water targets that received only poor coverage of spray. These targets tended to have fewer water droplets and more smaller droplets compared to the average target in this water:oil spray mixture class. Thus the water:oil spot size ratio was probably reduced by the treatments chosen for analysis.

Results for the dilute mixture of 1:50 are shown in figure 4. In laboratory experiments we sprayed the WSP and OSP to achieve good coverage on the WSP, but with less than 20% coverage, so spot size could be measured without too many overlapping spots. Under these spray conditions, we found that the number of oil spots on targets sprayed with both nozzles with oil:water mixture ratio of 1:50 was too low to conduct spot size comparisons with spots on WSP. For the dilute mixtures, we observed that water droplets less than 300 μm in diameter did not produce an oil spot large enough to observe with the image setup used in this analysis. To achieve a large number of measurable spots on OSP at mixture ratios on the order of 1:50 or greater requires a population of water spots that is too dense for accurate spot size measurement.

Field experiments selected for analysis at these mixture ratios were even more skewed toward poorly sprayed targets and so results are not reliable for reasons given in the discussion of 1:10 results. Results for the most dilute mixture of 1:10 were similar to those for the 1:50 mixture ratio and are not shown here.

**SUMMARY AND CONCLUSIONS**

This study attempted to use oil- and water-sensitive papers collected in a study of air-blast spray deposition in and between citrus trees to determine water:oil spot size ratios for sprayed oil:water mixtures from 1:5.9 to 1:100. Because much less oil than water was sprayed, it was hoped that oil spots would not touch or overlap as much as water spots and the decreased spot density would allow improved sensitivity in comparing spray deposits using different sprayer treatments. Because oil spots have a much greater spread factor than water spots, when volume mixture ratios are less than 1:10, oil spots and water spots are about the same size. However for mixture ratios of 1:50 and 1:100, water spot diameters are expected to be about three to six times greater than oil spot diameters.

It is likely that spot sizes on OSP will be less suitable for estimating water spots sizes on WSP for large water spots, as oil sometimes separates into two or more globules as the water drops dry and then forms two or more oil stains instead one. With heavy spray coverage, where drops coalesce, this problem will probably be increased. However this problem should not greatly affect spray parameters such as area covered or spray volume calculated from spots on OSP targets.

Conclusions are:
- Water:oil spot diameter ratios measured from the field sprayed WSP and OSP did not agree well with predicted
water:oil spot diameter ratios. Measured ratios increased,
whereas calculated ratios were predicted to decrease with
increasing water spot size.

- Water:oil spot diameter ratios measured for the laboratory
sprayed WSP and OSP were similar to predicted ratios.
Thus it appears to be possible to measure WSP and OSP
spread factors in the laboratory and to conduct laboratory
spray trials to confirm calculated water:oil spot ratios are
near calculated values.

ACKNOWLEDGEMENTS
The authors wish to thank Zhaohong Xian and Barry Nudd
for technical assistance with measuring spot sizes.

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